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ANALYSIS

# Why economic dynamics matter in assessing climate change damages: Illustration on extreme events

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ABSTRACT

Extreme events are one of the main channels through which climate and socioeconomic systems interact, and it is likely that climate change will modify the probability distribution of the losses they generate. The long-term growth models used in climate change assessments, however, cannot capture the effects of such short-term shocks. To investigate this issue, a non-equilibrium dynamic model (NEDyM) is used to assess the macroeconomic consequences of extreme events. This exercise allowed us to define the *economic amplification ratio*, as the ratio of the overall production loss due to an event to its direct costs. This ratio could be used to improve the cost–benefit analysis of prevention measures. We found also that, unlike a Solow-like model, NEDyM exhibits a bifurcation in GDP losses: for each value of the capacity to fund reconstruction, GDP losses remain moderate if the intensity and frequency of extremes remain under a threshold value, beyond which GDP losses increase sharply. This bifurcation may partly explain why some poor countries that experience repeated natural disasters cannot develop. Applied to the specific issue of climate change, this model highlights the importance of short-term constraints in the assessment of long-term damages, and shows that changes in the distribution of extremes may entail significant GDP losses in absence of specific adaptation. It suggests, therefore, that to avoid inaccurately low assessments of damages, researchers must take into account the distribution of extremes instead of their average cost and make explicit assumptions on the organization of future economies.

## 1. Introduction

Modelers who assess economic impacts of climate change face a dilemma that has been very frankly presented by William Nordhaus (1997): "*After 500 years, [global average temperature] is projected to increase by 6.2 °C over the 1900 global climate. While we have only the foggiest idea of what this would imply in terms of ecological, economic, and social outcomes, it would make most thoughtful people – even economists – nervous to induce such a large environmental change. Given the potential for unintended and potentially disastrous consequences, it would be sensible to consider alternative approaches to global warming policies.*" It is thus not only

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outsiders of mainstream economics (e.g., Azar and Schneider, 2003) who question the legitimacy of the very low percent of GDP losses estimated by the published assessments of climate change damages (e.g., Peck and Teisberg, 1992; Nordhaus, 1998; Mendelsohn et al., 2000; Tol, 2002a,b), and the consequently unambitious optimal abatement trajectories suggested by these studies.

Part of the problem comes from the fact that the quantification of impacts is still in its infancy. First, many important sectors and types of impact are not treated by published studies (IPCC, 2001a). Second, most studies evaluating optimal abatement trajectories envisage only certainty cases, in which we know exactly the future climate. Hedging strategy approaches show that inserting uncertainty about climate sensitivity and the possibility of singularities in the damage function suffices to justify significant departures from reference emissions trends, even if the most-likely damage level remains moderate (Ambrosi et al., 2003; Yohe et al., 2004).

But another part of the problem may lie in the description of the dynamics of the economic growth. Since resorting to long-term growth model is made necessary by the time horizon of the climate change issue, economists unsurprisingly rely on extensions of the Solow model (e.g., Nordhaus, 1994). These models, however, describe economies moving along balanced pathways and do not examine their readjustment in response to exogenous shocks. They consequently neglect the fact that welfare losses resulting from a given amount of climate change impact may be drastically different, would it fall on prosperous economies or on economies weakened by various disequilibria or experiencing inertia in their readjustment process.

This paper aims at framing the orders of magnitude at stake. It compares economic consequences of a given climate impact falling on economies similar in all respects, except that one follows an equilibrated growth pathway while the other experiences transient disequilibria. We take extreme events in Europe as an example, because they are one of the most documented channels through which climate and economy interact, and because the order of magnitude of this interaction is significant enough to support an aggregate analysis.

In the first section we present a model, NEDyM (Non-Equilibrium Dynamic Model), which reproduces the behavior of the Solow model over the long term, but which allows for disequilibria during transient phases. The second section explains how available information *about large-scale extreme weather events* can be translated in economic terms. The third section describes the calibration and validation of NEDyM and the three following sections apply NEDyM and present comparative exercises.

## 2. A dynamic model to capture unbalanced growth pathways

NEDyM models a closed economy, with one representative consumer, one producer, and one good, used both for consumption and investment[3]. This aggregate representation presents the drawbacks of the absence of sector-based or geographical differentiation, but has the advantage of being similar to the Solow model. This makes it easy to reproduce the 'after shock' behavior of a Solow model and to compare it with the behavior of an economy with adjustment difficulties towards the same 'after shock' equilibrium. Compared with larger Computable General Equilibrium (CGE) models or to the World Bank RIMSIM model, this compactness also allows us to conduct more easily sensitivity analyses, regarding climate change or assumptions on economic dynamics.

We explain below the main changes applied to the basic Solow model, starting with its core set of equations where $Y$ is production; $K$ is productive capital; $L$ is labor; $A$ is total productivity; $C$ is consumption; $S$ is consumer savings; $I$ is investment;$\Gamma_{\text{inv}}$ is the investment (or, equivalently, saving) ratio; $\tau_{\text{dep}}$ is the depreciation time; and $L_{\text{full}}$ is the labor at full-employment:

$$\frac{dK}{dt} = I - \frac{K}{\tau_{\text{dep}}}, \tag{1}$$

$$Y = f(K, L) = AL^{\lambda}K^{\mu}, \tag{2}$$

$$C + I = Y, \tag{3}$$

$$L = L_{\text{full}}, \tag{4}$$

$$S = \Gamma_{\text{inv}}Y, \tag{5}$$

$$I = S. \tag{6}$$

NEDyM introduces the following changes to this generic structure:

(1) *Goods markets*: a price $p$ and a goods inventory $G$ are introduced, opening the possibility of temporary imbalances between production and demand instead of a market clearing at each point in time ($Y$=$C$+$I$, Eq. (3)):

$$\frac{dG}{dt} = Y - (C + I). \tag{7}$$

This inventory[4] encompasses all sources of delay in the adjustment between supply and demand (including technical lags in producing, transporting and distributing goods). Its situation affects price movements:

$$\frac{dp}{dt} = -p \cdot \left(\alpha^1_{\text{price}} \cdot \frac{Y - (C + I)}{Y} + \alpha^2_{\text{price}} \cdot \frac{G}{Y}\right). \tag{8}$$

Thus price adjustments operate non-instantaneously and the conventional market clearing conditions are verified only over the long term.

(2) *Labor market*: a nominal wage $w$ is introduced and the producer sets the optimal labor demand $L_e$ that maximizes

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[3] A comprehensive description of NEDyM is available online. URL:www.centrecired.fr/forum/rubrique.php3?id_rubrique=71.

[4] The goods inventory should be interpreted as the difference with an equilibrium value. A positive value indicates temporary overproduction; a negative value indicates underproduction.

profits as a function of real wage and marginal labor productivity:

$$\frac{w}{p}=\frac{\mathrm{d}f}{\mathrm{d}L}(L_e,K). \tag{9}$$

But full-employment is not guaranteed at each point in time such as in Eq. (4) ($L=L_{\mathrm{full}}$) because (i) institutional and technical constraints create a delay between a change in the optimal labor demand and the corresponding change in the number of actually employed workers:

$$\frac{\mathrm{d}L}{\mathrm{d}t}=\frac{1}{\tau_{\mathrm{empl}}}(L_e-L); \tag{10}$$

and (ii) wages are partially rigid over the short-term; they progressively restore the full employment rate by increasing (resp. decreasing) if labor demand is higher (resp. lower) than $L_{\mathrm{full}}$,

$$\frac{\mathrm{d}w}{\mathrm{d}t}=\frac{w}{\tau_{\mathrm{wage}}}\frac{(L-L_{\mathrm{full}})}{L_{\mathrm{full}}}. \tag{11}$$

(3) *Household behavior*: as Solow (1956), NEDyM uses a constant saving ratio but it makes the tradeoff between consumption and saving ($S=\Gamma_{\mathrm{inv}}Y$, Eq. (5)) more sophisticated by considering that households (i) consume $C$, (ii) make their savings available for investment through the savings $S$, and (iii) hoard up a stock of money $M$, that is not immediately available for investment[5].

(4) *Producer behavior*: instead of automatically equating investments and savings ($I=S$, Eq. (6)), NEDyM describes an investment behavior "*à la* Kalecki (1937)". It introduces a stock of liquid assets held by banks and companies which is filled by the difference between sales $p(C+I)$ and wages ($wL$) and by the savings received from consumers ($S$). These assets are used to redistribute share dividends[6] (*Div*) and to invest ($pI$). This formulation creates a wedge between investment and savings.

$$\frac{\mathrm{d}F}{\mathrm{d}t}=p(C+I)-\mathrm{wL}+\mathrm{S}-\mathrm{Div}-\mathrm{pI}. \tag{12}$$

The dynamics of the system is governed by an investment ratio which allocates these assets between productive investments and share dividends:

$$I=\Gamma_{\mathrm{inv}}\cdot\frac{1}{p}\cdot\alpha_{\mathrm{F}}F. \tag{13}$$

$$\mathrm{Div}=(1-\Gamma_{\mathrm{inv}})\cdot\alpha_{\mathrm{F}}F. \tag{14}$$

**Table 1 – NEDyM steady state (net flows) and EU-15 economic variables in 2001 according to Eurostat (2002)**

| Symbol | Description | Steady state | observed values |
|---|---|---|---|
| Y | Production (=demand) | 9 | 8.8 |
| *L* | Percentage of employed workers | 93% | 92.6% |
| *wL* | Total annual wages | 6 | 5.6 |
| C | Consumption | 7 | 6.8 |
| S | Available savings | 2 | 1.8 |
| *Div* | Share dividends (i.e. all investor's gains) | 3 | 3.2 |
| *I* | Physical investment | 2 | 1.8 |

Values are in thousands of billions of euros.

This ratio is such that the redistributed dividends satisfy an exogenous required return on equity $\rho$ demanded by the shareholders. This describes a specific growth regime under which producers invest the amount of funds available when the required amount of dividends have been paid[7].

$$\frac{\mathrm{d}\Gamma_{\mathrm{inv}}}{\mathrm{d}t}=\begin{cases}\alpha_{\mathrm{inv}}(\gamma_{\max}-\Gamma_{\mathrm{inv}})\cdot\left(\frac{\mathrm{Div}}{p\cdot K}-\rho\right) & \text{if}\ \frac{\mathrm{Div}}{p\cdot K}-\rho>0\\ \alpha_{\mathrm{inv}}(\Gamma_{\mathrm{inv}}-\gamma_{\min})\cdot\left(\frac{\mathrm{Div}}{p\cdot K}-\rho\right) & \text{if}\ \frac{\mathrm{Div}}{p\cdot K}-\rho\le 0\end{cases}. \tag{15}$$

The model is calibrated so that the benchmark equilibrium is the economic balance of the European Union in 2001 (EU 15), assuming that the economy was then in a steady state.[8] Table 1 compares the value of this steady state with the observed values from Eurostat (2002). This steady state is consistent with a Solow-like growth model with a constant savings ratio set at $\Gamma^{*}_{\mathrm{save}}=22\%$. With a growth rate of productivity A of 2% per year, the model predicts that production increases by 3% a year under full employment and that labor and capital incomes grow regularly.

To understand better the model response to shocks, Fig. 1 displays the responses of NEDyM and its 'Solowian' equivalent, both without productivity growth, to a 10% instantaneous decrease in the productivity coefficient *A*. It shows that the transient frictions are responsible for a stronger economic shock in NEDyM than in the Solow model. In NEDyM the production drop is amplified by the fact that, because of price and wage rigidities, lower labor productivity leads to a lower employment rate. The decrease in profits reduces the re-invested share of savings; the resulting reduction in consumption and investment lead to a Keynesian amplification of the initial shock. At the apex of the re-adjustment process, two years after the shock, unemployment is 3% higher than its equilibrium level. Employment returns to equilibrium 10 years later and is followed by a slight overshoot due to inertia.

If productivity is reduced by the same 10%, but progressively instead of instantaneously, the NEDyM behavior tends to align with the Solow behavior. Instead of a 3% increase in underemployment, a progressive decrease in productivity spread out over 20 or 40 years causes only a small additional underemployment, of 0.5% and 0.2%, respectively. At the infinite limit, if

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[5] The existence of this stock is justified both by the preference for liquidity and precautionary savings, and by practical constraints, since this stock of money is needed to carry out the economic transactions.

[6] In NEDyM the share dividends encompass all investment benefits: dividends, revenues from bonds, sales of assets, capital gains, spin-offs to shareholders, repurchase of shares.

[7] Other economic regimes are possible, for example a "managerial economy" in which the priority is given to investments: managers redistribute then to shareholders the amount of funds available when all profitable investments have been funded.

[8] Obviously, the economy of EU-15 was not on a steady state in 2001; but this approximation is made acceptable by the weak sensitivity of the NEDyM behavior and of our results to small differences in the base year equilibrium.

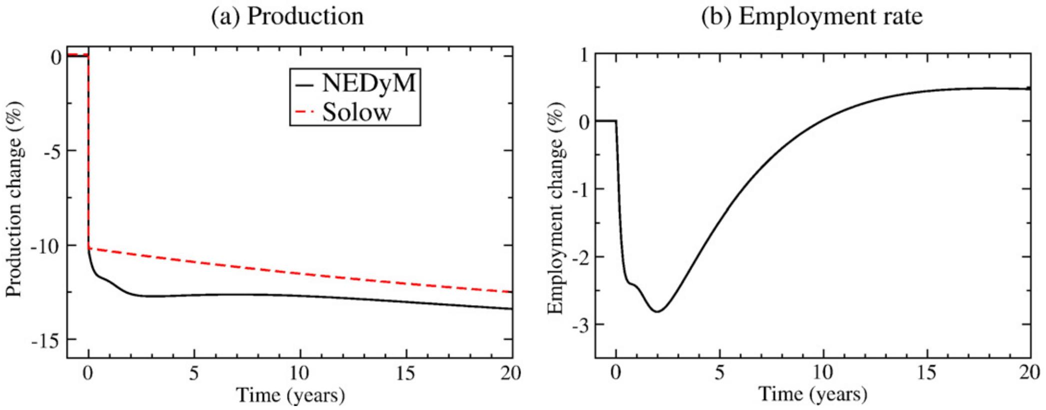

**Fig. 1 – Model response to a 10% decrease in productivity, for NEDyM and the Solow model. Over the long term, both models have the same final state.**

the time scale of the productivity decrease is longer than the model characteristic times, there is neither additional underemployment nor changes in the investment ratio and NEDyM is equivalent to the Solow model.

## 3. Modeling economic impacts of Large-scale Extreme Weather Events (LEWE)

There is no strict scientific definition of Large-scale Extreme Weather Events (LEWE); they are rather characterized by their media impact and their capacity to generate sudden and large social concerns[9]. We will define them as rare climate events causing important capital destructions over time period ranging from one day (cyclones) to several weeks (floods).

Less media-impressive gradual changes (e.g. a progressive ill-adaptation of infrastructure and housing (Hallegatte et al., in press)) may ultimately be responsible for larger damages than extreme events. We concentrated however on the latter because (i) they attract attention to the linkages between short-run responses to shocks (capital destruction, breakdown of electricity or drinking water supply) and long-term dynamics; (ii) they are poorly represented in current integrated assessment models (Goodess et al., 2003) and far more documented than other types of climate impacts.

### 3.1. *Data on costs of LEWEs and climate change predictions*

Insurance and re-insurance companies keep records of damages caused by major weather catastrophes. According to Munich-Re (2003), their frequency increased by a factor 4.4 between the 1960s and the 1990s and the corresponding economic losses by a factor 7.9. These statistics reflect a better reporting of disasters and the existence of more assets in vulnerable places (e.g. coastal areas). Assuming that the distribution of extremes did not change significantly since the sixties (IPCC, 2001b, chap. 2) leads to a multiplication by 1.8 of the mean economic losses per event, corresponding to an increase of 2% per year of the cost of the representative LEWE. This figure is close to the economic growth rate over the period, suggesting that, even though frequencies increased, natural intensities were constant and costs increased as the income level.

There are bodies of research suggesting that climate change will modify economic costs of LEWEs. First, changes in the mean trajectory of strong storms, even with the same frequency and intensity, would suffice to cause higher damages by impacting regions not currently adapted to them. Second, meteorological conditions that are considered as extremes today will become more frequent. Beniston (2004) and Déqué (2004a) suggests that the exceptional heat wave in Europe in 2003 could be a good proxy for the average summers in the latter part of the 21st century. Along the same line, Déqué (2004b) measures heat-wave risks as the average number of days per year during which the maximum daily temperature exceeds 30 °C for at least 10 consecutive days. During the 1960–1999 period, this index was lower than one in the large majority of France and lower than 5 in the whole country. But is predicted to be multiplied by up to 20 in 2071–2100. It will be, therefore, larger than 5 in most of the country and larger than 30 in the south-east. This dramatic increase is caused, in part, by the higher mean temperature, but also by an increase in temperature variability (Schär et al., 2004). The same concerns exist about the occurrence of severe flooding in Europe (Christensen and Christensen, 2003) and in the U.S., or about the destructiveness of tropical cyclones (Emanuel, 2005; Webster et al., 2005). Choi and Fisher (2003) suggests that, *ceteris paribus*, the annual precipitation increase with a doubling of atmospheric $CO_2$ concentration would increase U.S. losses due to flooding by about 100% to 250% and losses due to hurricanes by 150% to 300%.

### 3.2. *Definition of LEWE in numerical experiments*

We focus here on four types of LEWE: floods, winter storms (and the corresponding storm surges), droughts and heat waves. Following Katz et al. (2002), we characterize them through three criteria:

(1) A minimum threshold for the magnitude of economic losses. According to Munich-Re (2004) or Swiss-Re (2004), floods in Germany in 2002 caused direct damages[10]

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[9] Examples of such events are the 2002 floods in Germany or the recent landfall of Katrina in New Orleans.

[10] All these figures represent only direct losses.

amounting to 10 G€, spread out between infrastructure (4 G€), trade and industry (2 G€), household (2 G€) and others (2 G€). According to the same source, the Mississippi floods in 1993 in the U.S. caused 18 G€ losses and the winter ’99 windstorms over Europe around 20 G€ losses (Munich-Re, 2002). Swiss-Re (1998) shows that the Netherlands exhibits a 30 to 60 G€ flood damage potential and a 100 G€ damage potential in case of storm surge. The flash-floods in the south of France are at the other end of the spectrum of events that are considered as catastrophic with a typical cost around 1 G€ per event (e.g., the flooding of Nimes in 1999). Given these orders of magnitude we set the minimum threshold for an LEWEs at 0.01% of the GDP of the EU 15, which corresponds to damages amounting to 0.80 G€.

(2) The probability of a LEWE exceeding this threshold over a one-month period. Taking the last 20 years as representative of the statistical distribution of climate events and assuming that their distribution was stationary during this period and that LEWEs are independent, the probability of occurrence over one month of a weather event causing more than 0.8 G€ of losses is $p_{EE}=0.06$, using data from Munich-Re (2004). For simplicity sake, we assume that there is at most one LEWE in one month, even though examples exists of the contrary (e.g. the two winter-storms in Europe in December 1999).

(3) The probability density function (PDF) of the losses due to a single LEWE. The link between the natural intensity and economic losses of LEWE is still a very open question because (i) losses do not increase regularly with natural intensity, but involve thresholds, including the maximum economic loss potential of each impacted area[11]; (ii) adaptation measures will reduce LEWE costs as their frequency or intensity increase.

Assuming that the economic loss PDF exhibits a power tail, however, is consistent both with (Katz et al., 2002) and with Fig. 2, which shows the empirical distribution of single-LEWE economic losses, ranked in four categories based on Munich-Re’s assessments. To work with a tractable function, therefore, we will assume that the PDF of the LEWE economic losses is a Weibull distribution and is given by (for $s>s_{EE}$).

$$f_{\beta,\chi}(s) = \beta\cdot\chi^{\beta}\cdot(s{-}s_{EE})^{\beta-1}\cdot\exp(-(\chi(s{-}s_{EE})^{\beta})) \tag{16}$$

The fit gives $\chi=0.897933333$ and $\beta=0.000178672$, and the corresponding Weibull distribution[12] is reproduced in Fig. 2.

### 3.3. Modeling costs of capital losses

Disasters mainly destroy the stock of productive capital and a natural modeling option to represent their consequences is to consider that they reduce instantaneously the total productive capital ($K\to K-\Delta K$). This option, hereafter referred to as *H1*, amounts to treating an after-disaster economy as equivalent to an economy in which past investments were lower. We discuss hereafter three biases resulting from this option and propose modeling alternatives to avoid them.

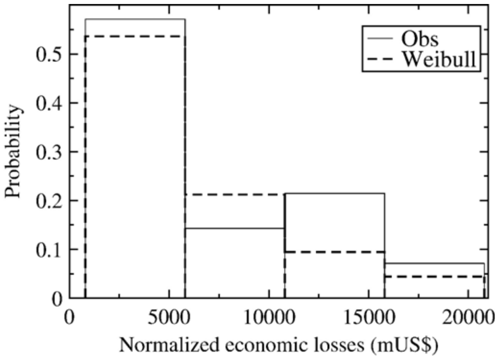

**Fig. 2 – Histogram of weather event probability with respect to economic losses, in 4 ranges, for the observations (*Obs*) and the fitted-Weibull distribution $f_\zeta$ (*Weibull*).**

(1) Because of decreasing returns in the production function, considering that an after-disaster economy is equivalent to an economy with lower past investments amounts to assuming that capital destructions affect only the less efficient capital. In a Cobb–Douglas function ($Y=AL^{\lambda}K^{\mu}$), the “after LEWE” production would be $Y_1=AL^{\lambda}(K_0-\Delta K)^{\mu}$, and a $x$% loss of equipment would reduce the production by less than $x$% (see Fig. 3).

To account for the fact that LEWEs may affect any capital stock, independently of its productivity, we modified the Cobb–Douglas production function by introducing a term $\xi_K$, which is the proportion of non-destroyed capital. This new variable $\xi_K$ is such that the *effective capital* is $K=\xi_K\cdot K_0$, where $K_0$ is the *potential productive capital*, in absence of LEWE. The new production function is[13]:

$$Y_2=\xi_K\cdot f(L,K_0)=\xi_K\cdot A\cdot L^{\lambda}\cdot K_0^{\mu} \tag{19}$$

With this new production function, a $x$% destruction of the productive capital reduces production by $x$% (see dashed-line in Fig. 3).

(2) The replacement of the productive capital $K$ by the two new variables $K_0$ and $\xi_K$ makes it necessary to modify the modeling of investment and to introduce the distinction

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[11] An evaluation of such potential of losses for some extreme events and some regions is proposed by Swiss-Re (1998).

[12] To assess the sensitivity of our results to the specification of the distribution function, we also tested a linear fit (see below).

[13] We rewrite the Cobb–Douglas production function as:

$$Y=f(L,K_0)=\int_0^{K_0}\partial_2 f(L,k)\cdot dk, \tag{17}$$

where $\partial_2 f$ is the derivative of $f$ with respect to the productive capital. To describe a situation where equipment are equally affected independently of their productivity, we adopted the following specification:

$$Y=\int_0^{K_0}\partial_2 f(L,k)\cdot\xi_K\cdot dk=\xi_K f(L,K_0)=\xi_K\cdot A\cdot L^{\lambda}\cdot K_0^{\mu} \tag{18}$$

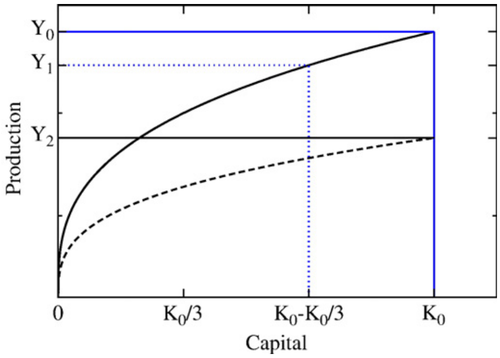

**Fig. 3 – Production with respect to productive capital for different hypotheses. The solid line shows the production given by a Cobb–Douglas production function. In hypothesis** *H1*, **when one-third of productive capital is destroyed by a disaster,** *K* **is decreased and the production function is unchanged: production is thus reduced from $Y_0$ to $Y_1$. In** *H2* **or** *H3*, **such a disaster change the production function from the solid line to the dashed line, without changing** *the potential productive capital* $K_0$. **Production is, therefore, reduced from $Y_0$ to $Y_2$, which is much lower than $Y_1$.**

between regular investments, carried out to increase the production capacity, and reconstruction investments that follow a disaster[14]. Denoting $I_n$ the investments that increase the potential capital $K_0$, and $I_r$ the reconstruction investments that increase $\xi_K$, we can write:

$$\frac{dK}{dt} = \frac{d\xi_K}{dt}\cdot K_0 + \xi_K \cdot \frac{dK_0}{dt} = I_r + \left(I_n - \frac{1}{\tau_{dep}}\cdot K\right), \quad (20)$$

which leads to:

$$\frac{\partial K_0}{\partial t} = \frac{-1}{\tau_{dep}} K_0 + \frac{I_n}{\xi_K} \quad (21)$$

$$\frac{\partial \xi_K}{\partial t} = \frac{I_r}{K_0} \quad (22)$$

Assuming that, when $\xi_K<1$, investments are first devoted to replace the destroyed capital – because these investments have higher returns – leads to:

$$I_r = \begin{cases} \min(I, (1-\xi_K)\cdot K_0) & \text{if } \xi_K < 1 \\ 0 & \text{if } \xi_K = 1 \end{cases} \quad (23)$$

We can then easily derive $I_n$ from :

$$I_n = I - I_r \quad (24)$$

This hypothesis will be hereafter referred to as *H2*.

(3) Most importantly, short-term constraints play an important role in disaster aftermaths, by slowing down the reconstruction process. Past LEWEs are found to have destroyed only a small amount of capital by comparison with annual investments, suggesting a recovery spread out over at most a couple of months. But past experience suggests that short-term constraints reduce the reconstruction pace. For example, the 10 G€ of reconstruction expenditures after the 2002 floods in Germany, corresponding to 10 days of German investments, have been spread out over more than 3 years. One source of friction is that consumers, insurance and re-insurance companies, other companies and public organizations need time to direct high amounts of money to reconstruction activities. This constraint is crucial in developing economies (Benson and Clay, 2004). Another source of friction is that the sectors involved in reconstruction activities have skills and organizational capacities adapted to the normal state of affairs and cannot face huge increases in demand (after the French storms in 1999 or after the AZF explosion in Toulouse, reconstruction took several years because roofers were not numerous enough).

**Table 2 – Summary of the different hypotheses on disaster modeling**

| Hypothesis | Description |
|---|---|
| *H1* | Cobb–Douglas production function<br>No distinction between productive investments and reconstruction investments |
| *H2* | Modified Cobb–Douglas production function<br>Distinction between productive investments and reconstruction investments<br>No limitation of the reconstruction investments |
| *H3* | Modified Cobb–Douglas production function<br>Distinction between productive investments and reconstruction investments<br>Limitation of the reconstruction investments at $f_{max}$ % of the total investments |

To capture how these constraints may impact the pathways back to the equilibrium, we bounded by $f_{max}$ the fraction

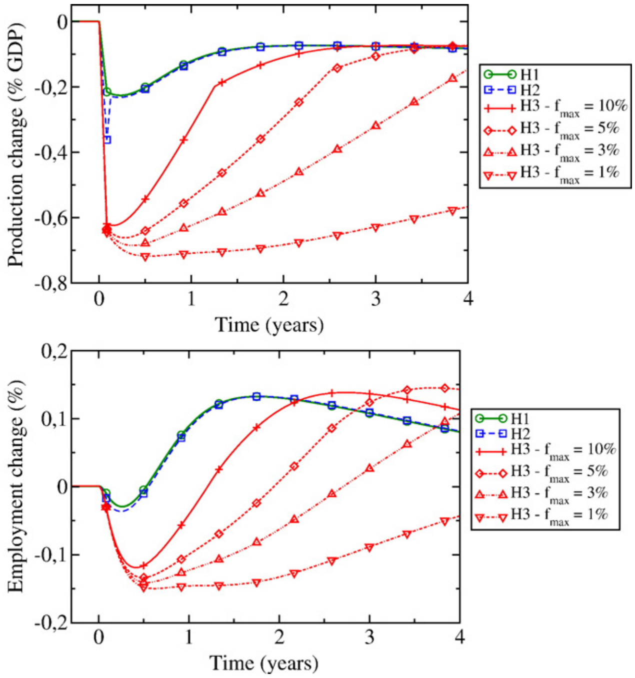

**Fig. 4 – Production and employment changes in response to a disaster destroying capital amounting for 2.5% of GDP, in the classical hypothesis** *H1* **(only the less efficient capital disappears),** *H2* **(capital disappear equally with respect to its efficiency) and** *H3* **(reconstruction investments are limited).**

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[14] This distinction has been introduced by Albala-Bertrand (1993).

of total investment that reconstruction investments can mobilize. This last specification will be referred to as *H3*.

$$\begin{cases} I_n = I - I_r \\ I_r = \begin{cases} \min(f_{\max}\cdot I, (1-\xi_K)\cdot K_0) & \text{if } \xi_K < 1 \\ 0 & \text{if } \xi_K = 1 \end{cases} \end{cases} \qquad (25)$$

A value $f_{\max}=5\%$ means that the economy can mobilize about 1% of GDP per year for the reconstruction i.e. about 90 G€ per year for EU-15. This order of magnitude can be compared with other efforts diverting investments from productive activities such as the 1.2% of U.S. GDP spent yearly for the Vietnam war and the 0.5% for the 1990–1991 war in Iraq. One per cent of GDP for a specific reconstruction activity thus represents a significant effort. It is worth noting that reconstruction is strongly dependent on the level of cost-sharing in the economy. When considering a small region that can benefit from significant exterior resources for its reconstruction, the amount of reconstruction investments can reach values far higher than 5%.

## 4. Calibration and validation: the economic amplification ratio

To validate these modeling options, a disaster was applied to the economy at steady state in the NEDyM model, with the set of hypotheses summarized in Table 2. This disaster destroys the stock of productive capital by an amount equivalent to 2.5% of GDP. This amount is comparable (in relative terms) with the 1999 Marmara earthquake, the consequences of which have been well documented and estimated between 1.5 and 3.3% of GDP (World Bank, 1999; OECD, 2003).

Fig. 4 shows the economic responses to this disaster under the modeling frameworks *H1*, *H2*, and *H3* with different values of $f_{\max}$: 10%, 5%, 3%, 1%. It shows first that the maximum intensity of the shock is multiplied by 2 in *H2* compared with *H1*. The gap between these two hypotheses, however, lasts a very short period of time, because all investments capacities are immediately devoted to reconstruction, making the situations in both hypotheses equivalent a few months after the disaster.

The difference between *H2* and *H3* is more significant because the duration of the production losses spans from a few months in *H1* and *H2* to several years in *H3* with $f_{\max}=1\%$. Fig. 5 shows that the growth rate is reduced by 0.2% the year of the disaster in *H1* and *H2*, and by between 0.5 and 0.7% in *H3*. Two years after the disaster, the growth rate is higher than baseline with all assumptions but *H3*-1%, because of both the catching-up effect and the economic boost from reconstruction activities. This increase in growth rate vanishes progressively in subsequent years.

The model response that is the most consistent with observations of the Marama earthquake is produced using the *H3* hypothesis and $f_{\max}=5\%$: *"In terms of indirect costs, the World Bank team estimates that the earthquake will reduce GNP in 1999 by 0.6 percent–1.0 percent. […] In the year 2000, GNP growth is expected to exceed baseline forecasts by some 1 percent of GNP due primarily to reconstruction activity."* (World Bank, 1999)[15]. Under the H3-5% hypothesis, NEDyM is able to reproduce this aftershock macroeconomic behavior. It reproduces the two-year reconstruction duration, the growth rate reduction the year of the disaster and the 0.6% GDP reduction during the first year. The 0.2% production growth (over baseline) found by the model the following year seems underestimated, but it is difficult to validate the model more rigorously: the impact of a disaster on the national account aggregates is generally much smaller than the underlying economic variability (e.g. Albala-Bertrand, 1993) and the specifics of the pre-shock Turkish economy are a major cause of the strength of the recovery[16].

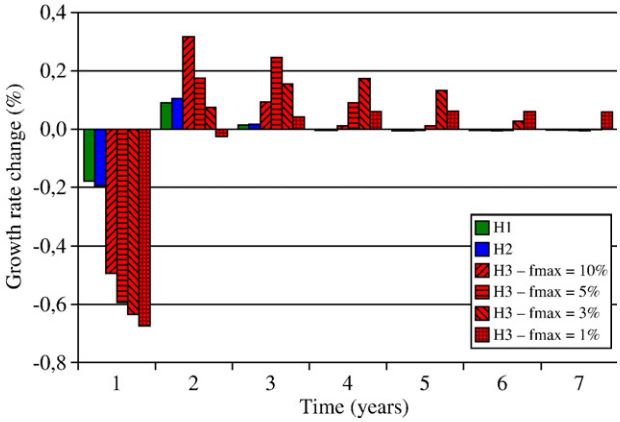

**Fig. 5 – Changes in economic growth due to the disaster, year per year, for the different hypotheses.**

With $f_{\max}=5\%$, the disaster, which causes direct losses amounting to 2.5% of GDP, leads to a total production loss of 3% of initial GDP, spread over more than 10 years. This assessment defines an Economic Amplification Ratio, namely the ratio of the overall production losses due to the disaster to its direct losses. In this case, this ratio is 3/2.5=1.2.

This economic amplification ratio depends on the disasters destructiveness and on the hypothesis used to model disasters and reconstruction. This dependency is illustrated by Table 3, that shows, for hypotheses *H1*, *H2* and *H3* with $f_{\max}=10\%$, 5%, 3% and 1%, the total production losses due to a disaster responsible for direct costs amounting to 0.25%, 0.5%, 2.5% and 5% of GDP. It confirms that there is no significant difference between *H1* and *H2* and that reconstruction constraints are not significant when coping with relatively small events. It shows also that taking into account reconstruction constraints changes in a drastic manner the estimation of total production losses due to large-scale events[17]. In our best-guess hypothesis

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[15] These figures are confirmed by estimates from the OECD and from the Turkish Industrialists and Businessmen Association (TUSIAD) (see OECD, 2003).

[16] It has been suggested (e.g., OECD, 2003) that the replacement of the destroyed capital by more recent capital would increase the productivity after the disaster. This conclusion, however, is very controversial (Benson and Clay, 2004). More convincing is the argument that the Turkish economy was in recession before the shock, with a 7% decrease in GDP the year preceding the Marmara earthquake, and that there were a lot of excess capacity capable of supporting the stimulating effect of the reconstruction works. This latter effect will be investigated in a follow-up paper.

[17] The practical difficulties met during the New Orleans reconstruction after the Katrina's landfall provide an illustration of this effect, that will probably make the overall cost of Katrina be much larger than its direct cost.

**Table 3 – Total production losses in % of GDP, due to a disaster responsible for direct costs amounting to 0.25%, 0.5%, 2.5% and 5% of GDP, as a function of the modeling hypothesis**

| Direct costs (% GDP) | Modeling hypothesis | | | | | |
|---|---|---|---|---|---|---|
| | H1 | H2 | H3 | | | |
| | | | $f_{\max}=10\%$ | $f_{\max}=5\%$ | $f_{\max}=3\%$ | $f_{\max}=1\%$ |
| 0.25 | 0.21 | 0.21 | 0.22 | 0.22 | 0.23 | 0.26 |
| | (0.85) | (0.86) | (0.86) | (0.88) | (0.91) | (1.03) |
| 1.25 | 1.04 | 1.04 | 1.14 | 1.26 | 1.41 | 2.18 |
| | (0.83) | (0.83) | (0.91) | (1.01) | (1.13) | (1.75) |
| 2.5 | 2.07 | 2.08 | 2.51 | 2.98 | 3.60 | 6.64 |
| | (0.82) | (0.83) | (1.00) | (1.19) | (1.44) | (2.66) |
| 5.0 | 4.12 | 4.27 | 5.98 | 7.86 | 10.32 | 22.06 |
| | (0.83) | (0.85) | (1.20) | (1.57) | (2.06) | (4.41) |

The numbers in parentheses are the Economic Amplification Ratios.

of $f_{\max}=5\%$, the total production losses due to a disaster with direct costs amounting to 5% of GDP reach 7.9% of GDP, i.e. an economic amplification ratio of 1.6, almost twice as high as the one calculated without taking into account reconstruction limitations (*H1* or *H2*).

## 5. The macroeconomic costs of LEWEs

In this section, we conduct numerical experiments to assess how the macroeconomic costs of LEWEs depend on the way they are represented and the way the "growth engine" of the economy is modeled. First, we do so under assumptions of stable LEWE distribution and second, under changing distributions. This requires the use of a 400 years time period, because we need a representative set of very rare LEWEs. Obviously, the aim is not to reproduce a realistic economic trajectory over such a long period, but rather to provide insights on the macroeconomic costs of the current and future LEWE distribution.

### 5.1. *Macroeconomic costs due to the current LEWE distribution*

The LEWE distribution calibrated in Section 3.2 is used to generate a set of LEWEs. It exhibits a mean annual direct cost of about 0.05% of GDP, i.e. 4.6 G€ per year at present GDP. These direct costs lead to GDP losses of a comparable amount – between 0.05% and 0.06% – in a Solow-like model and in NEDyM.[18] This equivalence shows (i) that, in NEDyM, the deepening of the short-term production losses due to Keynesian processes is roughly compensated by the booming effect of the subsequent reconstruction, and that (ii) the current economic capacity to fund and carry out reconstruction (i.e. $f_{\max}$) is large enough not to represent a binding constraint. This is not surprising, since developed economies have adapted their reconstruction capacity to the currently observed distribution of events.

But, whereas they predict the same averaged production losses, the difference between NEDyM and a Solow-like model is that the latter cannot be actually perturbed by shocks, since it is only valid over the long-term. The productive capital, therefore, has to be reduced at each point in time by a constant amount[19], this amount being equal to the mean annual direct cost of the LEWEs. As a consequence, the Solow model does not assess transition costs to return to equilibrium after each event. In NEDyM, since transitions are explicitly modeled, we can look at event-per-event losses (Fig. 6) and capture the magnitude of adjustment processes and the variability of GDP around its mean value, variability which has a welfare impact and may even generate social crisis.

### 5.2. *Economic vulnerability to changes in the LEWE distribution*

Let us now examine the hypothesis under which either climate change or changes in the localization of physical assets and populations raise the frequency or the direct losses due to LEWEs.

To do so, we carry out a sensitivity analysis, using both the Solow-like model and the NEDyM model, by modifying:

- The extreme event probability, which is multiplied by $\alpha_p$

$$p_{EE} = \alpha_p \cdot p^0_{EE}, \qquad (26)$$

- The pdf of the losses, such that mean loss is multiplied by $\alpha_z$:

$$f(s) = \beta \cdot \chi^\beta \cdot \left(\frac{s - s_{EE}}{\alpha_z}\right)^{\beta-1} \cdot \exp\left(-\left(\chi\left(\frac{s - s_{EE}}{\alpha_z}\right)^{\beta}\right)\right). \qquad (27)$$

For simplicity's sake, the frequency and the mean cost of the LEWEs are both multiplied by the same amount ($\alpha_p=\alpha_z$), equal to one of six values {1, 2, 3, 4, 5, 6}. Note that, when $\alpha_p=\alpha_z=6$, the average direct cost of extreme events is multiplied by as much as 36.

Moreover, since GDP losses depend strongly on $f_{\max}$ in NEDyM, and given that this ratio may change in the future and that poor countries may have far lower reconstruction capabilities than those captured by our 5% best-guess assumption (Benson and Clay, 2004), we carried out simulations with ten values of $f_{\max}$, ranging from 1% to 10%.

The simulations carried out with a Solow-like model (not shown), which are independent of $f_{\max}$, yield a linearly growing amount of production losses as the intensity and frequency of LEWEs rise: from 0.05% when $\alpha_p=\alpha_z=1$ to about 2% when $\alpha_p=\alpha_z=6$.

Fig. 7 represents the averaged annual production loss due to LEWEs after 100 years, as calculated by NEDyM, with respect to the value of $f_{\max}$ and to the value of $\alpha_p$ and $\alpha_z$. The interesting finding in NEDyM is that, unlike in the Solow-like model, there exists a threshold line: for each value of $f_{\max}$, LEWE damages remain limited if $\alpha_p$ and $\alpha_z$ are lower than a certain value, beyond which losses increase sharply.[20] The red

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[18] The same simulation, carried out with a linear pdf instead of the Weibull pdf leads to production losses of the same order of magnitude(0.05%).

[19] Practically, through an increase in the depreciation rate of capital.

[20] Other simulations in which we vary independently $\alpha_p$ and $\alpha_z$ (not shown), show that the same type of bifurcation also occurs when only one of these parameters exceeds a threshold value, the other one being fixed.

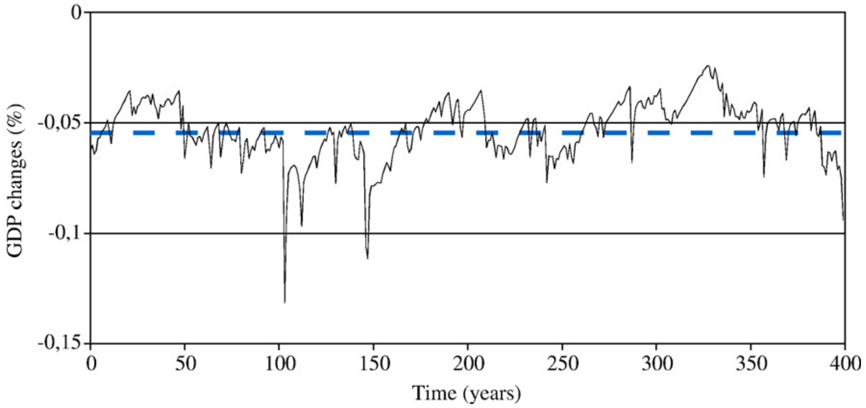

Fig. 6 – Production change due to the current LEWE distribution in NEDyM.

line in Fig. 7 shows, for each value of $\alpha_p$ and $\alpha_z$, the minimum value of $f_{\max}$ that maintains the GDP losses below 1% of GDP. Such bifurcation in GDP losses arises when reconstruction investments cannot cope with the amount of damages because the financial or technical constraints represented by $f_{\max}$ become binding. In this case, the fraction of capital destroyed $(1-\xi_K)$ does not return to zero between events and the economy remains in perpetual reconstruction, preventing any significant increase in the potential capital $K_0$, i.e. any economic development.

This highlights that, even though the macroeconomic consequences of weather extreme events are in most cases small, a sequence of such events can have long-term consequences, especially on poor countries. The fact that the joint effect of extreme events and constraints on reconstruction capabilities can be strong obstacles to economic development has already been stressed by Gilbert and Kreimer (1999) and Benson and Clay (2004). Our results suggest that extreme events may even contribute to bifurcations towards poverty traps: because they face regular extreme events and do not have the financial capacity to rebuild their infrastructure quickly enough after each shock, these countries cannot accumulate productive capital. As an example, Guatemala experienced an impressive series of weather catastrophes[21] that severely inhibited economic development. In the same region, the Honduran prime minister said that the single hurricane Michele in 2001 "*put the country's economic development back 20 years*" (IFRCRCS, 2002).

Additionally, our model suggests that modifications to the distribution of extremes – due to climate change or to changes in asset localization – can entail significant GDP losses. More generally, climate change damages cannot be assessed without explicit hypotheses about the economic organization of future societies, including social structure, spatial scale of disaster cost-sharing, quality of infrastructure maintenance, insurance and reinsurance regulations (e.g. existence of the *Solvency* package of the EU that aims at increasing the solvency margins of the insurance sector), and existence of specific funds to cope with disasters (e.g. the Florida Hurricane Catastrophe Fund or the French *Cat-Nat* system).

## 6. Conclusions

The basic message of this paper is that the assessment of climate change damages depends strongly on assumptions about the functioning of the economy on which the impacts will fall. This demonstration is made through a modeling framework capable of representing (i) non-equilibrium dynamics in a way that makes the model equivalent to the neoclassical Solow growth model over the long-term; (ii) realistic short-term constraints on the post-disaster reconstruction process.

This exercise also allowed us to define the *Economic Amplification Ratio* as the ratio of the overall production loss due to an event to its direct costs. We showed that for large-scale events, this ratio can be significantly larger than one. As a consequence, even in the present climate, this ratio should be used by policymakers to assess the benefits of mitigation or prevention measures, in order to take into account the second-order impacts of disasters in cost–benefit analyses. For instance,

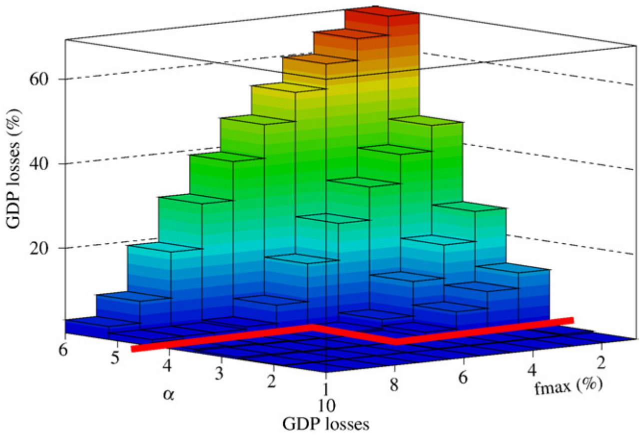

**Fig. 7 – Mean GDP losses due to LEWEs after 100 years, in percent of GDP, with respect to the value of $f_{\max}$ (in %) and to the value of the LEWE parameters ($\alpha_p = \alpha_z$). The red line separates the parameters for which the GDP losses are below 1% of GDP.**

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[21] Hurricane Mitch in 1998, 3 years of drought from 1999 to 2001, and hurricane Michele in 2001.

since it seems likely that the overall cost of the Katrina's landfall in New Orleans will be much larger than its direct cost, it would be justified to take into account the economic amplification ratio in a cost–benefit analysis of the New Orleans flood protection system (see Hallegatte, 2006).

Applied to extreme event distributions, this modeling showed that production losses due to extreme events depend, with strong non-linearity, both on the characteristics of the distribution and on the capacity to conduct reconstruction after each disaster. This capacity does not depend only on funding capacity; it depends also on the technical and organizational constraints limiting the capacity to spend money in a productive manner over the short term. In an economy with non-equilibrium phases, and for a given distribution of extremes, there is a bifurcation value for the capacity to reconstruct, under which mean GDP losses increase dramatically.

This paper highlights the importance of short-term processes and constraints in the assessment of long-term damages due to extreme events. It shows that in the case of high intensity shocks (like extreme events) with a certain frequency and probability distribution, the ultimate costs may be higher than suggested by sole consideration of the mean value of impacts. Applied on the specific issue of climate change, it suggests that assessing future damages requires both taking into account the distribution of extremes instead of their average cost, and making explicit assumptions about the organization of future economies.

These results are tentative, but they indicate, as a research priority, the incorporation of uncertainty about future economic organization in climate change damage assessments, in addition to climate uncertainty. Achieving a better understanding of the implications of this uncertainty will, however, require advances in the modeling of short-term/long-term interactions in economics.

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